Correlated charge detection for read-out of a solid state quantum computer

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The single electron transistor (SET) is a prime candidate for reading out the final state of a qubit in a solid state quantum computer. Such a measurement requires the detection of sub-electron charge motion in the presence of random charging events. We present a detection scheme where the signals from two SETs are cross-correlated to suppress unwanted artifacts due to charge noise. This technique is demonstrated by using the two SETs to detect the charge state of two tunnel junction - coupled metal dots, thereby simulating charge transfer and readout in a two qubit system. These measurements indicate that for comparable buried dopant semiconductor architectures the minimum measurement time required to distinguish between the two charge states is of the order of 10 ns.

Quantum computers (QCs) hold promise to unveil unprecedented computational power by exploiting quantum mechanical principles such as superposition and entanglement[1]. Of the many proposals to implement such machines, architectures based on the manipulation of quantum two-level systems (qubits) in the solid state are appealing due to their scalability and ease of integration with existing micro-electronics hardware[2,3,4]. However, the coupling of solid state qubits to a classical system for the purpose of read-out remains a formidable challenge, amounting to the detection of single charge or spin states in the presence of background artifacts. Several recent proposals for solid state QCs make use of the extreme charge sensitivity of single electron transistors (SET) to infer the state of a qubit either via direct detection[5,6] or by sensing a spin-dependent charge transfer event[2,4]. Since in these cases the read-out signal is indeterministic, read-out schemes require good signal to noise without relying on the use of frequency selective (lock-in) or auto-correlation noise reduction methods.

Presently, the dominant decoherence mechanism for charge based qubits is $1/f$ background charge noise[7]. In order to overcome this limitation, qubit operations should occur at speeds well above the $1/f$ corner (3kHz), where the influence of background charge motion is reduced. The process of read-out however, is stochastic in nature and can potentially be affected by slow time-scale random-charging events close to or within the SETs. Such charging events are indistinguishable from real charge *signals* connected with read-out and constitute a strong challenge for single-shot projective measurements.

Here we focus on a read-out detection technique where the independent charge signals from two aluminum SETs are cross-correlated both temporally and spatially in order to greatly reduce the effect of spurious background charge noise. Previously Zorin *et al.,*[8] have made use of two SETs to identify and spatially resolve different *sources* of intrinsic charge noise associated with $1/f$ type trapping processes[9]. Here we use a similar technique not to discriminate between different noise sources, but as a means to distinguish the real *signal* from background artifacts with the fidelity required to read-out a quantum computer.

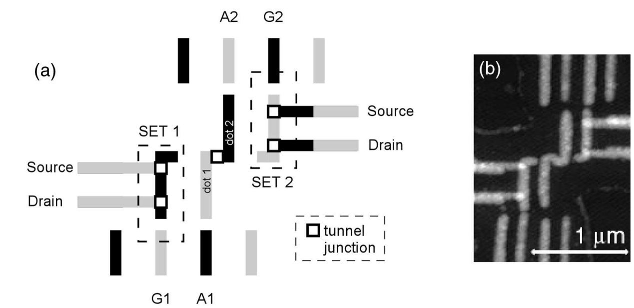

FIG. 1: (a) Schematic and (b) AFM image of a twin-SET device, fabricated by double-angle evaporation of Al with intermediate oxidation to form tunnel junctions.

To demonstrate an ability to detect a fraction of an electron charge, as required for qubit read-out, we have designed and fabricated an all-metal twin-SET/double-dot system (Figure 1). In this design two metal dots connected by a tunnel junction[10] simulate a solid state charge qubit. When an electron tunnels from dot1 to dot2, SET1 senses the departure of the electron, while SET2 simultaneously senses the arrival of the electron. Cross-correlation of the two signals permits suppression of all charging events except those that originate from the area in between the two SET detectors.

Devices were fabricated using electron beam lithography and a bi-layer resist process[11] on a phosphorus doped silicon substrate ($10\Omega cm$). The Al/AlO_x tunnel junctions were formed by standard shadow evaporation processes with an intermediate oxidation step. A thin native oxide layer was used in conjunction with the P-doped substrate to produce additional charge traps for the purpose of characterising our cross-correlation detection scheme. Note that although our device is engineered to contain additional charge traps, devices fabricated on high quality substrates are also influenced by background charge noise[12]. Measurements were performed in a dilution refrigerator with a base temperature below 30 mK, using standard lock-in techniques with excitation volt-

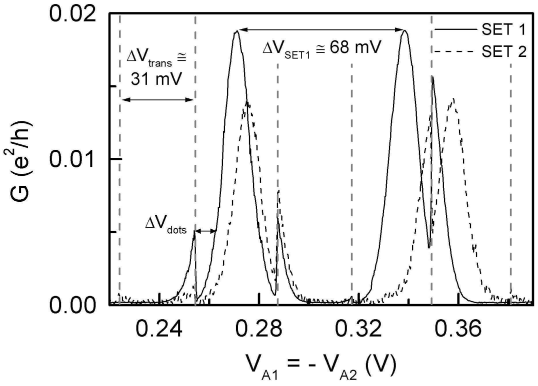

FIG. 2: Conductance of the two SETs as a function of differential A-gate bias $V_{A1} = -V_{A2}$. Electron transfer between the dots is seen as periodic 'jumps' in the conductance of both SETs as highlighted by the vertical dashed lines.

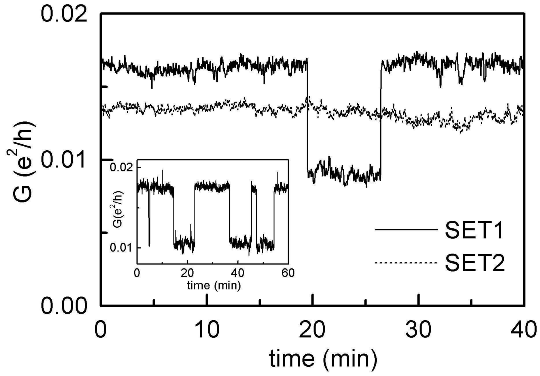

FIG. 3: Conductance of the two SETs as a function of time. The inset shows random telegraph signals (RTSs) associated with a charge trap close to SET1. The body of the figure shows a RTS occurring only in SET1 with the conductance of SET2 remaining constant.

ages of $10 - 50\ \mu V$. A magnetic field of 0.5 Tesla was applied to suppress superconducting effects in the aluminum nanostructures.

This device simulates read-out in a solid state quantum computer by using SETs to sense the controlled transfer of an electron from one metal dot to the other. Controlled electron transfer is achieved by differentially biasing gates A1 and A2 to create an electric field between the dots. As the field is increased, the potential difference between the dots becomes large enough for one electron to overcome the Coulomb charging energy of the double-dot system. Figure 2 shows the conductance of both SET1 and SET2 as a function of the differential A-gate bias. The bias gates induce conventional Coulomb blockade (CB) oscillations in both SETs as the electrostatic potential of the SET islands is varied. Superimposed on these oscillations are abrupt discontinuities or 'jumps' associated with charge transfer between the metal dots (vertical dashed lines in Fig. 2). The magnitude of these jumps depends on the transconductance of the SET. The combination of double-dot electron transfer and CB oscillations produces signals with two distinct periods: A differential gate bias of $\Delta V_{SET1} \simeq 68$ mV for SET1 and $\Delta V_{SET2} \simeq 82.5$ mV for SET2 corresponds to the addition of one electron onto the SET island, while a differential bias of $\Delta V_{trans} \simeq 31$mV is required to transfer an electron between the metal dots.

Having demonstrated the ability to detect controlled single electron transfer in the double-dot system, we now turn to the issue of charge noise. Figure 3 presents data taken on both SETs as a function of *time*, with all gate biases fixed. The data shown in the inset to Fig. 3 reveals the presence of random telegraph signals (RTSs) associated with the charging - decharging of traps in the vicinity of the SET island[13]. Note that for the data shown in the main body of the figure the conductance of SET2 remains constant and free of switching signals for the duration of the measurement. Taken on its own a single

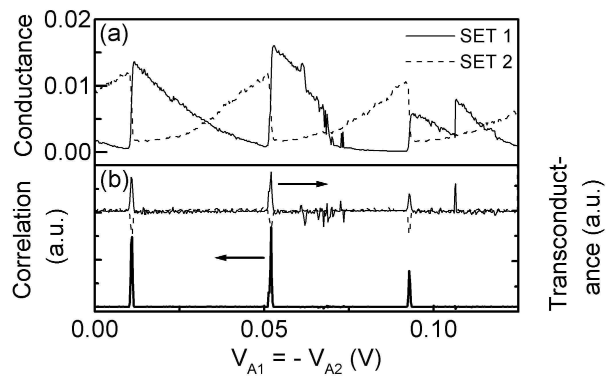

FIG. 4: **a)** Conductance of the two SETs as a function of differential A-gate bias, with direct coupling of V_{A1} and V_{A2} to the SETs removed by a compensating bias on G1 and G2. The characteristic sawtooth behavior results from controlled electron transfer between the metallic dots. **b)** Transconductance ($\partial G/\partial V_A$) and cross-correlation of the two SET signals to distinguish charge transfer events from background charge fluctuations.

RTS signal from SET1 would be inseparable from a true charge event associated with the transfer of an electron on the double-dot system. However, by correlating the signals from *both* SETs we are able to distinguish between readout events and background charge noise.

For efficient read-out the SETs should be operated at their maximum sensitivity, half way up a CB peak where the transconductance is largest. In order to achieve this while simultaneously continuing A-gate operations, the SET gate biases (G1 and G2) must be adjusted to compensate for the changing A-gate potential. Figure 4(a) shows data for both SETs where the direct coupling of the A-gate to the SETs has been compensated by adjusting gates G1 and G2. In this case the data for both SETs shows a clear periodic sawtooth, corresponding to

the transfer of single electrons between the metal dots. If both SETs are biased on the same side of a Coulomb blockade peak (eg on the rising edge) then their compensated signals move in *opposite* directions when a transfer event occurs. This is because SET1 senses the departure of an electron and SET2 senses its arrival. In contrast, signals that do not exhibit this behavior can be rejected as background charge noise. Figure 4(a) shows such an event occurring near $V_{A1} \approx 0.11V$. By correlating the signals from both SETs it is possible to reject all events except those signals arising from electron transfer between the metal dots. Figure 4(b) shows the correlation of signals by multiplying the transconductances ($\partial G_{SET1}/\partial V \times \partial G_{SET2}/\partial V$). A clear suppression of random charging events is achieved.

For SETs to be used to infer the state of qubits in QC architectures, the time required to perform a measurement must be less than the mixing time of the two level system (qubit). The ultimate limit to the SET's sensitivity is due to shot noise[14], which provides a lower bound for the time required to measure a charge Δq of $(t_{min})^{1/2} = 1.2 \times 10^{-6} e/\Delta q$. Therefore the amount of charge Δq induced on the SET island is a critical parameter characterising the efficiency of the read-out process, as it determines the time t_{min} required to distinguish the desired signal from the shot noise. For the simulation device presented here, the change in induced charge Δq due to the transfer of a single electron between the double dots can be determined from Fig. 2. We infer Δq by relating the lateral shift of the conductance G in A-gate bias due to a charging event, $\Delta V_{dot} \approx$8.1mV (SET1) and $\Delta V_{dot} \approx$7.1mV (SET2), to the gate bias required to add one extra electron to the SET island, $\Delta V_{SET1} \approx$ 68mV and $\Delta V_{SET2} \approx$ 82.5mV. For the data from SET1 in Fig. 2, Δq is estimated to be $\approx$8.1mV/68mV $\rightarrow \Delta q = 0.12$e (for SET2 $\Delta q = 0.086$e). Therefore a SET with a sensitivity approaching the quantum limit, would require a minimum measurement time t_{min} of order 10 ns to distinguish a single charge transfer event in the double-dot system from the shot noise, with a signal to noise ratio of 10 ($\Delta q = 0.01e$).

The minimum measurement time places significant practical constraints on solid state QC architectures, since the qubit to be read out with the SET must remain constant during the read-out process. For architectures utilising single dopants in a semiconductor, such as P in Si[2], numerical modeling[15] indicates that the capacitive coupling κ between the dopant and the SET is similar to that in our metal nanostructure, suggesting that the readout times will be comparable for the two cases.

In conclusion, we have demonstrated a charge detection scheme that makes use of cross - correlated signals from two SETs to suppress spurious noise associated with random trapping-detrapping events in the substrate and oxide. This scheme was demonstrated using an all metal twin-SET double-dot system to distinguish controlled electron transfer from random telegraph signals originating close to the SETs, and simulates readout in a solid state two-qubit system. Our measurements indicate that for comparative capacitive coupling, readout using a quantum-limited SET requires ≈10 ns to distinguish the readout signal with good signal to noise. Work is presently underway to construct twin radio frequency SET readout devices, so that this correlated measurement technique can be extended to much shorter timescales than presently demonstrated. We are also developing twin-SET devices in which the two metal dots are replaced with two clusters of localised P dopants buried in the silicon substrate, as a step towards the goal of creating a scalable P in Si quantum computer.

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